REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-04-

0110

1. REPORT DATE *(DD-MM-YYYY)*
01-30-2004

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*
11/01/2000 - 10/31/2003

4. TITLE AND SUBTITLE
3D Semiconductor Nanocavities

5a. CONTRACT NUMBER

5b. GRANT NUMBER
F49620-01-1-0021

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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20040225 159

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution Statement A: Approved for Public Release, Distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Nanocavities with a three-dimensional cavity mode confinement have been fabricated and their properties have been explored experimentally. Exhaustive measurements were made of linear and nonlinear transmission and reflectivity, and photoluminescence using cw and femtosecond lasers. The high quality of the oxide-aperture nanocavities containing a single quantum well resulted in a well resolved normal mode coupling and a record splitting-to-linewidth much larger than previously seen for a 3D photonic structure. The lateral confinement clearly suppresses guided modes responsible for a third peak evolving between the two normal modes in a planar microcavity; thus a longstanding mystery was solved. Lasing from microdisks containing quantum dots has been demonstrated at room and low temperature. A new design for a nanocavity has been developed; an air-bridge upper DBR mirror combined with an epitaxial apertured active region leads to a stronger three-dimensional cavity mode confinement. CW lasing from such a nanocavity occurred at room temperature. The coupling of a single quantum dot to a photonic crystal cavity has been investigated. In resonance the dot linewidth broadened considerably indicating the onset of the intermediate coupling regime.

15. SUBJECT TERMS
Nanocavity, quantum dots, QW lasers, normal-mode coupling

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE		7	19b. TELEPHONE NUMBER *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

3D Semiconductor Nanocavities

FINAL REPORT
November 2003

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US Air Force Office of Scientific Research
Grant No. F49620-01-1-0021

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Executive Summary

Summary of the Most Important Results

Oxide-Aperture 3D Semiconductor Nanocavities. A structure consisting of a bottom mirror, a spacer containing a narrow-linewidth single quantum well (SQW), and the first two layers of the top mirror was grown by MBE in Tucson. In Austin an oxide aperture was fabricated by photolithography, reactive ion etching, and oxidation, and the top mirror was completed by dielectric coatings; see Fig. 1. The aperture sizes ranged from 7μm down to 1μm in diameter. Several transverse modes could be observed for each

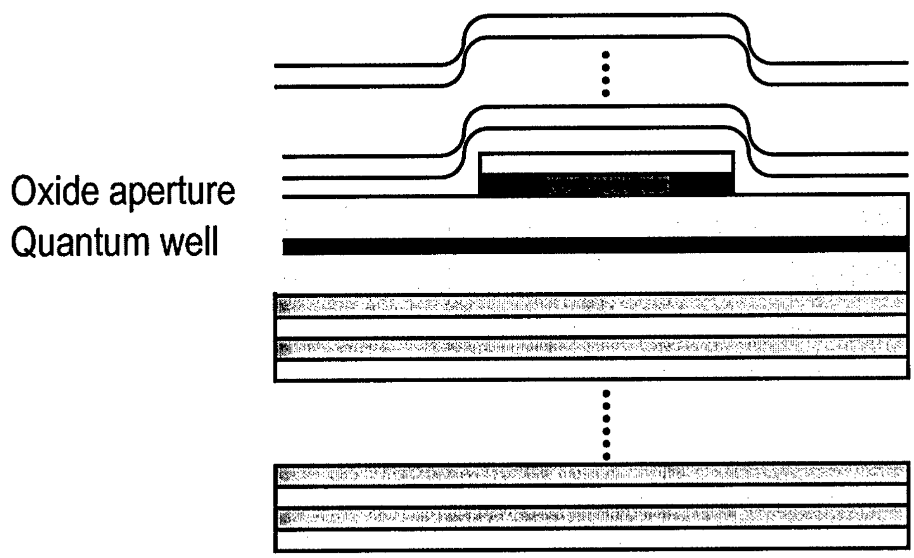

Fig. 1 Schematic of an oxide-aperture nanocavity containing a single quantum well.

aperture size. As expected for a three-dimensional mode quantization, the mode spacing increased with decreasing aperture diameter, see Fig. 2 left panel. To confirm the quantized nature of the photon mode we performed additional measurements with various angles of incidence with respect to the normal. While the spectral position of each transverse mode was preserved, the amplitudes of the high-order modes increased with increasing angle. The cavity quality factors Q (wavelength divided by the FWHM mode linewidth) for all aperture diameters were high enough to provide a clear normal-mode coupling even though Q degrades as the aperture size decreases. The high quality of the cavity together with the narrow exciton absorption line of about 0.6 meV FWHM resulted in well resolved normal mode coupling and a splitting-to-linewidth ratio of 4.9 at minimum splitting, much larger than previously seen for a 3D photonic structure; see Fig. 2 right panel. A typical normal- mode-coupling anticrossing behavior was seen, using different temperatures to tune the exciton resonance through the cavity mode [Lee et al. 01b].

The observation of such a well-defined normal-mode coupling (NMC) in a small optical mode volume allowed controlled nonlinear measurements. Present-day planar

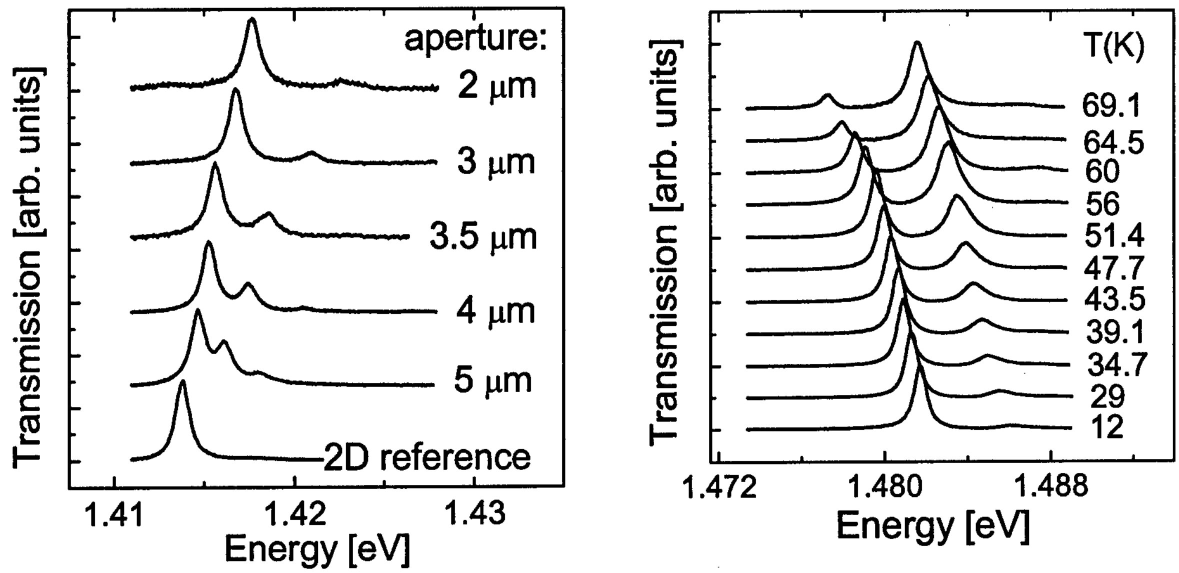

Fig. 2: Left panel: Transmission measurements demonstrating the 3D mode quantization. The mode spacing increases with decreasing aperture diameter. Right panel: Anticrossing mapped by temperature-tuning the exciton resonance through the cavity resonance.

microcavities are still far from the strong coupling regime. All previous experiments can be described using a classical light field or can be understood in analogy to a many-atom picture. As a first step towards the strong coupling regime, we investigated the quantum-well oxide-aperture nanocavities described above. Pump-probe experiments on these nanocavities revealed that the number of absorbed photons required for saturating the NMC peaks scales with the transverse area of the cavity mode and drops to 300 photons for an aperture diameter of 2 μm [Lee et al. 01a]. This is three orders of magnitude smaller than the 200,000 photons needed in a planar microcavity. Clearly, an important step has been made toward the quantum limit. Note that these measurements were made before we obtained the stable Cryovac system; they were possible because of the large separation between the 3D microcavities and the patience and tracking skill of the student.

Third-Transmission-Peak Mystery Solved. The availability of our SQW oxide-aperture nanocavity helped to solve a longstanding mystery seen in planar microcavities. Nonlinear measurements for an excitation resonant with the normal-mode peaks in a semiconductor microcavity show a very intriguing effect: a third peak in transmission (or a third dip in reflection) shows up between the two normal-mode peaks as the pulse energy is increased. It appears both in nonlinear fs single-beam experiments and in ps pump-probe experiments. Microscopic calculations (done by M. Kira and S. W. Koch) based on a quantized light description showed that quantum fluctuations give rise to intraband coherences if simultaneously an interband polarization and a pump-induced occupation of electron and hole states is present. These quantum correlations couple back to the interband polarization via guided modes. They contribute to the phase space filling and consequently to the macroscopic polarization. Our

measurements on an oxide-aperture nanocavity showed no third peak, thus confirming the important role of the guided modes in this effect. Additional measurements and calculations were performed to clarify the dependence of the third peak on the energetic position of the pump pulse and its spectral shape. The results were published in a Physical Review Letter [Ell et al 00, Brick et al.00, Brick et al. 01, Kira et al. 03].

Theory of Interface Fluctuation Quantum Dots. We have advanced the theory of interface fluctuation quantum dots. The question has been addressed of how the lifetime and dipole moment are related. The well known formula for the radiative decay of an atom in vacuum is modified for a quantum dot (QD) emitting in a semiconductor medium. There was a controversy about how this should be done: Two different relations are frequently used in the literature. A general formula has been derived valid for arbitrary refractive indices for the quantum dot and the surrounding medium for a quantum dot emitting in a semiconductor medium [Thränhardt et al. 02a]. It was shown that the relations used in the literature are limiting cases. For a quantum dot emitting into a semiconductor medium of about the same index, the formula approximately reduces to the simple formula that the dot radiative rate is just n times the vacuum rate.

The dipole moments of interface fluctuation quantum dots using actual growth parameters were computed and compared with measurements made by Duncan Steel's group at Michigan [Guest et al. 02]. The main uncertainty has to do with determining the quantum dot's size. The oscillator strength increases linearly with quantum dot area; but the energy separation between the lowest and next transition seen in PLE depends upon the longer of the side lengths, as well as upon broken symmetry that could open up forbidden transitions. Because of this lack of information, we have assumed that the dot is circular; this almost certainly overestimates the dot's size. In case of a circular dot the dipole moment scales with the quantum dot radius. The lifetime of the dot has been calculated, and a quadratic rise has been found for small dot sizes. For larger dot radii (about 100 nm) the rise starts to saturate towards the quantum well lifetime [Thränhardt et al. 02b, Thränhardt et al. 02c].

Air-bridge DBR Nanocavities (All-Epitaxial Apertured VCSEL). Based on the desire to increase optical coupling, we extended the aperture concept and developed a new design that employs air-gap DBRs made from alternating GaAs and air Bragg structures with etch and regrowth steps to form the lateral index confinement; see Fig. 3 This microcavity has the advantage of forming strong 3-dimensional confinement through the etched step within the microcavity laterally and the air-gap DBRs vertically, and strong 3-dimensional confinement through the InAs QD active material, which is selectively removed outside the aperture region. Luminescence from the etched regions showed a cavity resonance shift of about 21 nm due to the lateral shortening of the microcavity. This shift in the resonance indicates optical mode confinement in the lateral direction, similar to the oxide aperture. However, the confinement due to the etched step can be even greater than for the oxide-apertured nanocavities, and with the added advantages that there is no oxide strain and the aperture is lithographically defined. Calculations show that these microcavities can achieve Q's exceeding 20,000 with only a few mirror pairs.

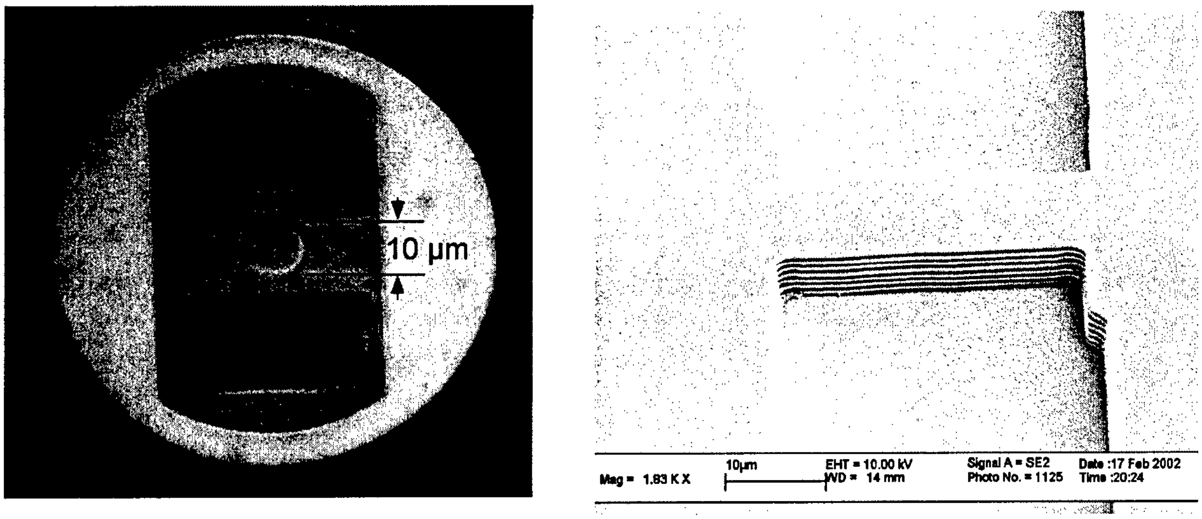

Fig. 3: Left panel: Top-view from an optical microscope of an all-epitaxial air-gap/GaAs VCSEL. The aperture diameter seen at the center of the image is 10 µm. The square etched regions provide access to the sacrificial AlGaAs layers of the upper DBR that are etched away. Right panel: Close-up of the air-gap top mirror.

A key step toward this type of microcavity has been achieved by fabricating an all-epitaxial apertured VCSEL that uses an air-bridge top mirror [Chen et al. 03]. The active region, which contains three InGaAs quantum wells, is centered in a full-wave spacer. The bottom DBR mirror consists of 31 n-doped GaAs/AlAs pairs. This initial work has been performed both to characterize the mirror with an optical cavity and to test the

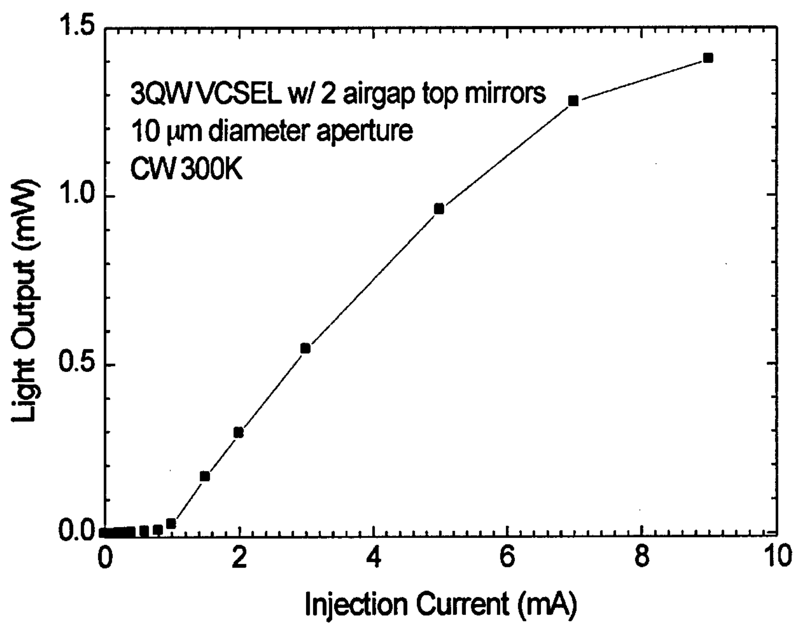

Fig. 4: Light vs. current curve for the air-gap/GaAs VCSEL of Fig.3.

suitability of the mirror and new aperture design for VCSEL's. The VCSEL uses only a two-pair air-gap/GaAs DBR as the upper mirror. Continuous-wave room temperature lasing was demonstrated [Chen et al. 03]. Both the threshold current and the threshold current density are found to be relatively low; see Fig. 4. They drop further when the number of upper air-gap/GaAs DBR layers is increased to three. By comparing the VCSEL performance with increasing pair number, the mirror loss was extracted. We found that the air-gap/GaAs DBR has a distributed loss of ~100/cm, which is quite large. We are still working to determine the source of this optical loss and to reduce it. It's possible that the loss mainly comes from the p-type doping, but it is also possible that the loss is due to optical scattering from around the all-epitaxial aperture. However, despite this loss in present structures, our research set the ground work for these new types of microcavities that can provide high-efficiency surface-normal emission and very small optical mode volumes. It is worth noting that we expect the device stability to improve as the device dimensions are reduced.

Lasing from a Microdisk. Microdisks with quantum dot active regions combine a small mode volume and a high-Q resonant cavity, the condition for a high spontaneous emission enhancement factor and a low lasing threshold. The samples were grown by Prof. Dennis Deppe, U. Texas – Austin, and fabricated into microdisks of about 2 μm and larger by Prof. John O'Brien, USC; see Fig. 5. The active region contained five layers of InAs quantum dots each with a high dot density. For the first time, lasing from a microdisk near 1300 nm at room temperature has been demonstrated [Yang et al. 03]. The Tucson measurements were performed in a Cryovac liquid helium cryostat with a built-in x-y nanopositioner stage. 2-D reflection images of the microdisk sample allowed us to find a specific microdisk again and again. Quality factors up to 11500 have been measured at low temperatures. Lasing at room temperature has been compared to lasing at low temperature from the same microdisk. Several whispering gallery modes spectrally overlap with the quantum dot transition geometry. Because the temperature shift of the dots is larger than that of the cavity modes a different cavity mode lases at low temperature. The most important result is the reduction in the threshold power of a factor of 2 when going from room to low temperature; see Fig. 6.

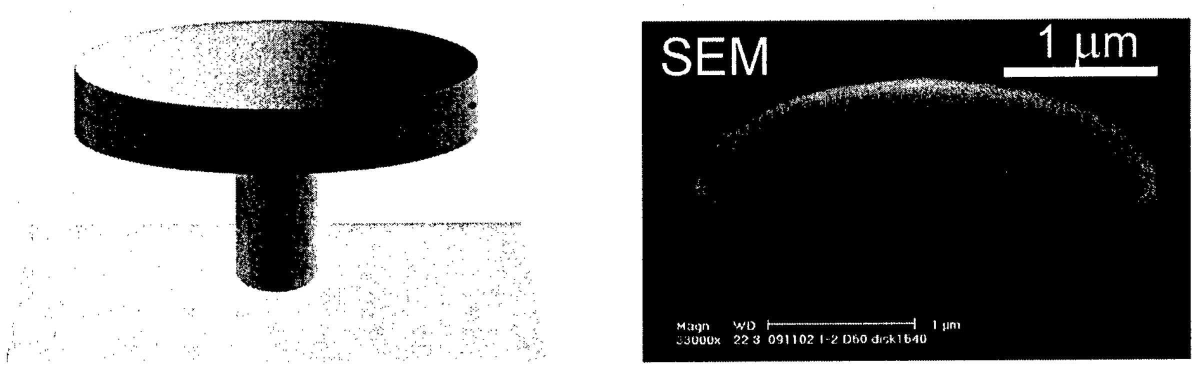

Fig.5: Schematic (left panel) and SEM image (right panel) of a microdisk.

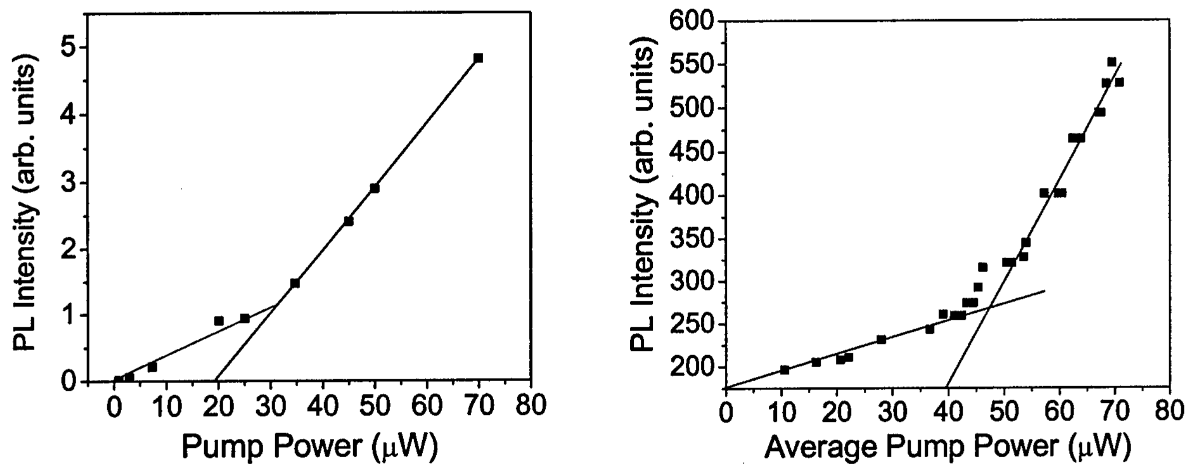

Fig. 6: PL intensity versus averaged pump power. Left panel: low temperature, right panel: room temperature.

Finding and refinding a given microdisk and staying centered on it for several minutes as needed for good data was made possible by the purchase of the Cryovac system as part of an AFOSR DURINT instrument grant. Another essential instrument for all of the low-light-level experiments, especially on a single quantum dot in the 1100-1300 nm range, was the InGaAs CCD linear array -- again made possible by the DURINT grant.

Intermediate Coupling Regime. The minimum volume optical cavity is one in which the light is confined to half a wavelength λ in the material in all three directions, i.e. $(\lambda/2)^3$; Axel Scherer and Tomo Yoshie at CalTech have fabricated photonic-crystal slab nanocavities with mode volumes as small as $2.5(\lambda/2)^3$; see Fig. 7. Each nanocavity contains a layer of InAs quantum dots grown by Dennis Deppe and Oleg Shchekin, U. Texas – Austin. Although the position of each quantum dot in the layer is random and its

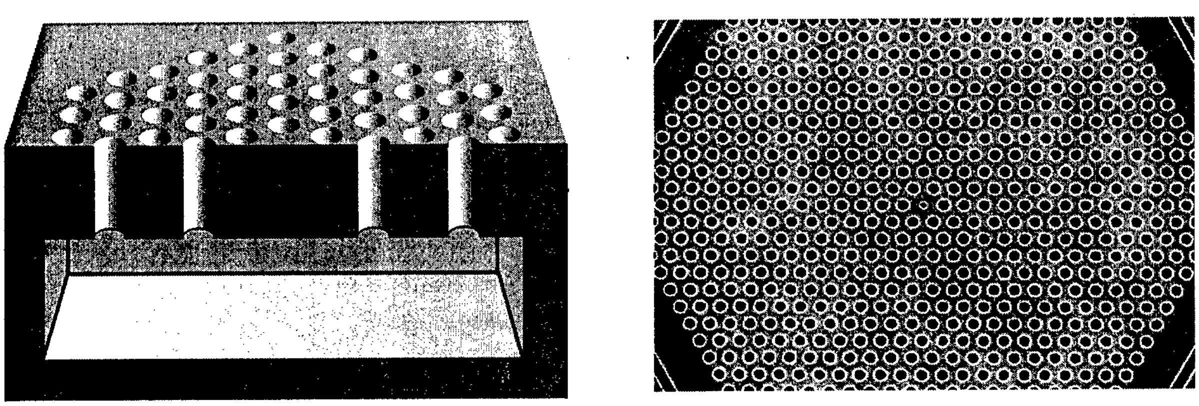

Fig. 7: Schematic (left panel) and SEM image (right panel) of a photonic crystal nanocavity.

transition energy somewhere within a 50-nm distribution, there is some probability that the transition energy of an individual dot and the nanocavity mode energy can be

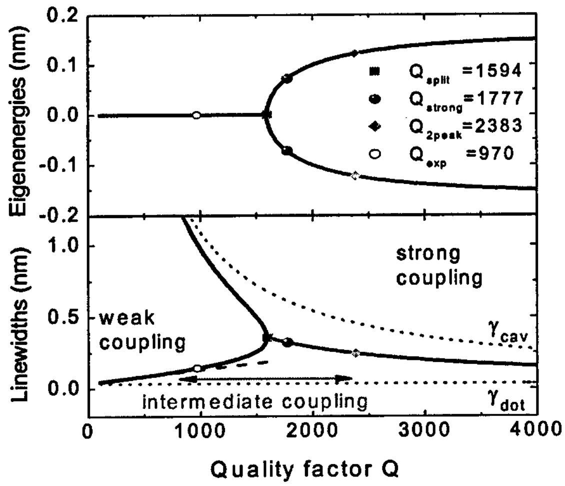

Fig. 8: Energies (upper panel) and FWHM linewidths (lower panel) calculated using the eigenvalue equation of the Jayne Cummings model for zero detuning. Experimentally deduced parameters are used. The dashed line in the lower panel shows the dot linewidth broadened by the enhanced spontaneous emission rate in the weak-coupling regime.

brought into resonance by temperature scanning. We have done just that using a nanocavity mode at 1085 nm with a Q of 970 [Yoshie et al. 03]. The measured PL linewidths as a function of the cavity-dot detuning were compared to calculated linewidths convoluted with the spectrometer function. Besides the measured uncoupled cavity linewidth and the measured uncoupled dot linewidth only the coupling strength entered the calculation as a fit parameter. Analysis showed that the measured linewidth of 0.141 nm at resonance exceeded the calculated linewidth characteristic for the weak coupling regime by at least 10%; see Figs. 8 and 9. In other words, the linewidth has begun to increase with Q more rapidly than the linear Purcell enhancement of the weak coupling regime. In fact we have reached the onset of intermediate coupling and are *only a factor of three away from strong coupling and quantum entanglement.* More recent photonic crystal nanocavity designs reduce the leak out the top (higher Q) and also have field antinodes accessible to quantum dots, giving reason to expect strong coupling to be seen in the near future.

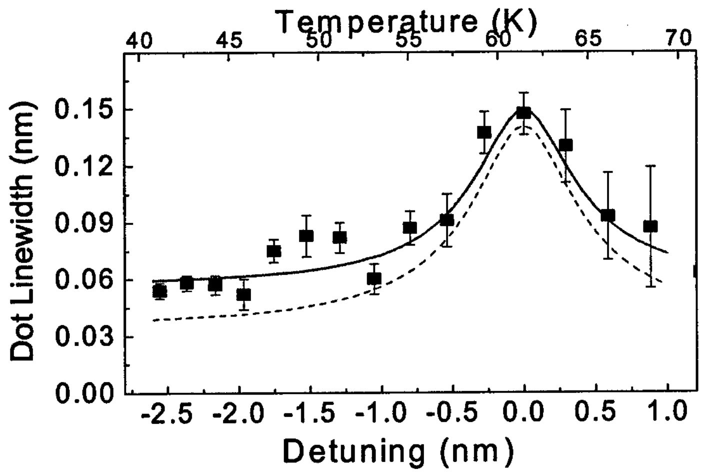

Fig. 9: *FWHM linewidth of the quantum dot (black squares) as a function of the dot-cavity detuning compared to calculated linewidths without (dotted line) and with (solid line) convolution with the spectrometer function.*

The fit value of the coupling is not unexpected. Using the calculated mode volume and maximum field-dot overlap of 0.5 of the maximum field, a Purcell factor of 46 was found. With this additional information a radiative lifetime of $\tau \leq 309$ ps was estimated, corresponding to dipole moment of 63 Debye. The latter is a reasonable value for a quantum dot transition.

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Participating Personnel and Advanced Degrees

Tucson: Graduate students partially supported by this grant: Eun Seong Lee; Peter Brick; Sorin Mosor, Greg Rupper; Sangam Chatterjee. Assistant Research Scientists: Jianfeng Xu, Angela Thränhardt. Associate Research Professor: Claudia Ell. Associate Professor: Galina Khitrova. Also associated with the research was Professor Hyatt Gibbs.

Austin: Graduate student supported by this grant: Qingwei Mo, Hua Huang, John Zou; Post doc: Manhong Zhang. Crystal growth technician: Terry Mattord. Professor: Dennis Deppe (IEEE LEOS Distinguished Lecturer – 2001/2002)

Inventions

None.